EXPERIMENTAL INVESTIGATION ON THE FEASIBILITY AND DURABILITY OF A NOVEL DIESEL PARTICULATE FILTER

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ABSTRACT

The increasing concerns on fuel prices, lowest fuel consumption, higher operating efficiency and low levels of carbon monoxide and unburned hydrocarbon during cold start have generated noticeable interest on diesel engine as a prime mover with expected higher soot and NO_X emissions. In order to reduce the emission from diesel fuelled vehicle, some control technologies were introduced. One of the technology is diesel particulate filter (DPF) which consists of a porous substrate that permits exhaust to pass through but traps particulate matter (PM) or carboneous soot. Conventional DPFs are manufactured using expensive materials. In this study, alternative material based on alumina and zeolite was used to form porous ceramics filter installed in diesel fuelled vehicle exhaust system and named as novel diesel particulate filter (NDPF). The NDPF elements were arranged in line with 1cm spacing inside an enclosed casing. The NDPF showed potential as DPF to curb soot emissions. Pressure drop for the NDPF was in the range of 89% - 93% at every given flow rate during pressure drop test. Effective soot reduction was in the range of 60% - 70%. As predicted, trapped soot were accumulated mostly at the front and middle of NDPF. Scanning electron microscope (SEM) and energy dispersive xray (EDX) analysis confirmed the trapping ability of carbon elements in the range of 19% - 70% for each filter. Brake specific fuel consumption (BSFC) and brake mean effective pressure (BMEP) was slightly affected when NDPF was installed in the exhaust system and resulted to drops in engine efficiency in the range of 2% - 26%. Nevertheless, further reinforcement steps for the NDPF are needed to prolong its filtering capacity.

ABSTRAK

Peningkatan kebimbangan terhadap harga minyak, penggunaan minyak yang terendah, kecekapan pengoperasian dan tahap karbon monoksida dan hidrokarbon yang rendah semasa permulaan enjin dihidupkan telah menimbulkan minat terhadap enjin diesel sebagai penggerak utama dengan kesan pengeluaran asap dan NO_X yang tinggi. Dalam usaha untuk mengurangkan pencemaran dari kenderaan berenjin diesel, beberapa teknologi untuk mengawalnya telah diperkenalkan. Salah satu teknologi adalah penapis partikel diesel (DPF) yang terdiri dari liang-liang berlubang yang pelepasan gas tetapi akan memerangkap partikel halus (PM) atau jelaga berkarbon. DPF konvensional dibuat menggunakan bahan-bahan yang mahal. Dalam kajian ini, satu bahan alternatif berdasarkan alumina dan zeolite telah dihasilkan untuk membentuk penapis seramik berliang dan dipasang pada sistem ekzos kenderaan berenjin diesel dan dinamakan sebagai penapis partikel diesel baru (NDPF). Elemen NDPF telah disusun sebaris dengan dipisahkan jarak sebanyak 1cm di dalam perumah. NDPF telah menunjukkan potensi sebagai DPF untuk mengurangkan pencemaran asap. Kejatuhan tekanan untuk NDPF adalah di dalam julat 89% - 93% dari setiap kadar alir yang dikenakan semasa ujian kejatuhan tekanan. Pengurangan asap pula di antara 60% - 70%. Seperti yang dijangka, asap yang ditapis kebanyakkannya berkumpul pada elemen hadapan dan pertengahan. Mikroskop pengimbas electron (SEM) dan analisis xray sebar tenaga (EDX) mengesahkan kemampuan untuk menapis elemen karbon dalam julat 19% - 70% untuk setiap penapis. Penggunaan bahan api tentu (BSFC) dan tekanan min berkesan (BMEP) sedikit terkesan apabila NDPF dipasang pada sistem ekzos dan menyebabkan pengurangan kecekapan enjin sebanyak 2% - 26%. Walaubagaimanapun, langkah pengukuhan lanjut untuk NDPF diperlukan untuk memanjangkan kapasiti penapisannya.

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LIST OF ABBREVIATIONS AND SYMBOLS

NDPF	-	Novel Diesel Particulate Filter
DPF	-	Diesel Particulate Filter
ΔP	-	Pressure Drop
λ	-	Lambda
sfc	-	Specific Fuel Consumption
HC	-	Hydrocarbon
CO	-	Carbon Monoxide
CO_2	-	Carbon Dioxide
NO_X	-	Nitrogen Oxide
SO_X	-	Suphur Oxide
ppm	-	Parts per millions
rpm	-	revolution per minutes
PM	-	Particulate Matter
BSFC	-	Brake Specific Fuel Consumption
SCR	-	Selective catalytic converter
NSR	-	NO_X storage-reduction
CRT	-	Continuously regeneration trap
CI	-	Compression Engine
TSP	-	Total suspended particulates
UTHM	-	Universiti Tun Hussein Onn Malaysia
BMEP	-	Brake mean effective pressure
SEM	-	Scanning Electron Microscope

EDX	-	Energy dispersive Xray
SOF	-	Soluble organic fraction
PAH	-	Polycyclic aromatic hydrocarbons
DI	-	Direct injection
TDC	-	Top death center
EGR	-	Exhaust gas recirculation
CAAA	-	Clean air act amendments
NHOG	-	Non-methane organic gas
NMHC	-	Non-methane hydrocarbons
TLEV	-	Transitional low emission vehicle
LEV	-	Low emission vehicle
ULEV	-	Ultra low emission vehicle
SULEV	-	Super ultra low emission vehicle
PZEV	-	Partial zero emission vehicle
HSU	-	Hartridge smoke unit
rw	-	Reference mass
AWASI	-	Area watch and sanction inspection program
IFQC	-	International fuel quality center
ASTM	-	American society for testing and materials
DOC	-	Diesel oxidation catalyst
ARB	-	Air resource board
DPNR	-	Diesel particulate NO_X reduction
Pt	-	Platinum
K	-	Kalium
Al_2O_3	-	Alumina
TiO_2	-	Titanium dioxide
Rh	-	Rhobium
ZrO_2	-	Zirconium oxide
ANN	-	Artificial neural network
FTP	-	Federal test procedure
NH_3	-	Ammonia

LNT	-	Lean NO_X trap
EEC	-	European economic community
PAZ	-	Porous alumina zeolite
Pu	-	Polyurethane
MOHE	-	Ministry of Higher Education, Malaysia
Cu-Zsm	-	Types of zeolite
AFR	-	Air fuel ratio
HP	-	Horse power
XRD	-	X-ray diffraction
LHV	-	Low heating value
Al	-	Aluminum
C	-	Carbon
O	-	Oxygen
Si	-	Silica
CPSI	-	Cells per square inch
η_e	-	Engine efficiency

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CHAPTER I

INTRODUCTION

In this chapter, the background and premise of the research is explained in details. It consists of the research background focusing towards the research study, problem statements, research objective, research scope and the significance of the research.

1.1 Research Background

Malaysia is a rapidly developing country working hard towards achieving its Vision 2020, of becoming a developed country. The increase in economic activities has also resulted to an increase in the country pollution problem. One of the main sources of the pollutants is emissions from motor vehicles, which is originated from incomplete fuel combustion; either diesel or gasoline. Statistic from Malaysia Road Transport Department shows that from 2003 until 2008, the total number of vehicle registered is 4.7 million. Mobile sources or motor vehicles include passenger cars, motorcycles, goods vehicles, taxis and buses which are among the contributors to air pollution especially in major cities. The same reports show that the numbers of vehicles registration in 2008 were increase than 2007 as show in Figure 1.1. These numbers will definitely increasing in coming years. The presence of these vehicles bring along the problem of air pollution because of the incomplete combustion by product that is emitted from engine exhaust pipe such as carbon monoxide (CO), hydrocarbon (HC), nitrogen oxide (NO_X), sulphur oxide (SO_X) and carbon soot (Department of Environment, Malaysia, 2008)

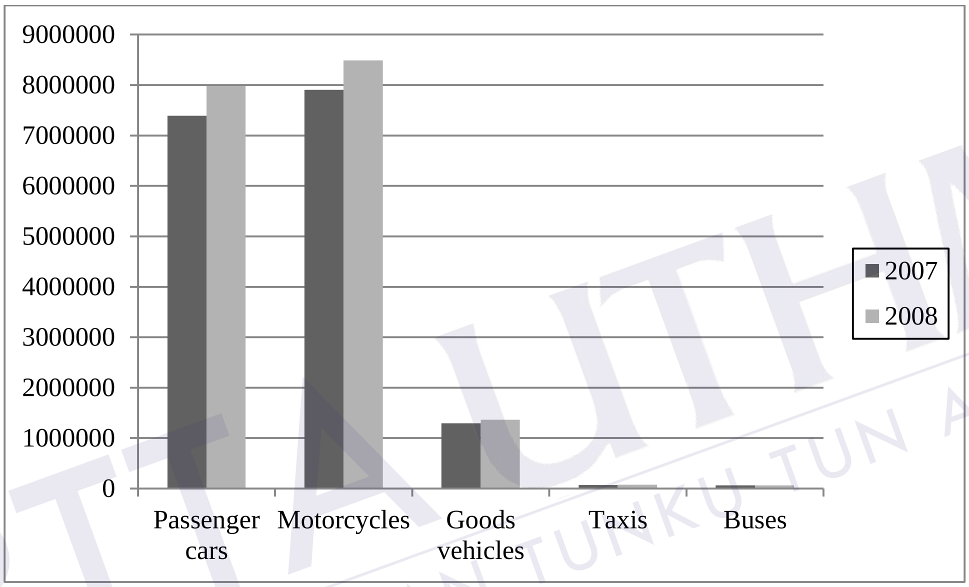

Figure 1.1: Number of registration vehicles in 2007 and 2008 (Department of Environment, Malaysia, 2008)

Air pollutant sources in Malaysia can be classified under four main sectors; motor vehicles, power stations, industries and other sources like open burning and trans-boundary sources (Department of Environmental, 2008). Motor vehicles are the main contributor for the CO and NO_X emission as show in Table 1.1. Meanwhile industrial sources are main contributor for PM about 40% and power station main contributor for SO_2 emission about 48%. Although Malaysia have a good environment to stabilize the pollutant, it has reached a critical level as witnessed during the past haze crisis (Zulkifli et al., 2002).

Table 1.1: Emissions load by motor vehicles 2008 (Department of Environment, Malaysia, 2008)

Emissions	Metric Tonnes	Percentage of others sources
SO_2	12,865	8
PM	4,557	14
NO_X	203,235	49
CO	1,410,134	97.1

Increasing concerns on the fuel prices, lowest fuel consumption, higher operating efficiency and low level of CO and HC during cold start have generated noticeable interests on diesel engine as a prime mover. It is classified as powerful, durable and reliable than gasoline engine. Nevertheless, diesel exhaust contain several pollutants that are harmful to public health and can also effect the environment through HC, NO_X, fine PM, CO and combination with other substance (Department of Environment, 2004).

Diesel engine operate with excess air ($\lambda > 1$) across their entire operating range, an insufficient quantity of excess air results in increased of PM (soot), CO and HC emission due of mixture formation. Others factor sources from engine compartment are combustion temperature, design of combustion chamber, injection timing, the rate of discharge curve, atomization of fuel and etc (Bosch, 2000).

In the diesel engine case, the major concern are about NO_X and PM. The development effort have been focused on reduction of engine out, exhaust aftertreatment and fuel formulation. The big challenges on this strategies are to maintain reduction formula. In the case of retarding injection timing would be effective in reduction of formation of NO_X, but it usually results in an increase in soot emissions and higher brake specific fuel consumption (BSFC) (Pundir, 2007). In other case, increasing fuel injection pressure can decrease soot emission but it can result in higher NO_X emissions (Pierpont & Reitz, 1995).

Another strategies by using advanced exhaust aftertreatment such as selective catalytic converter (SCR), NO_X storage-reduction (NSR) catalysts, diesel particulate filter (DPF) and continuously regenerating trap (CRT).

The DPF is a typical aftertreatment device for trapping soot particles contained in diesel engine exhaust gas. DPF is becoming an indispensable device to diesel engine vehicle. Numerous design of DPF involving different filter media and geometric configuration have been invented in the last 20 years (Konstandopoulos et al., 2000). It traps the particles when exhaust gases passed the porous structure. The filteration efficiency is more than 90%. Although some sort of clogging always occurs due to the particle trap, the consequent rise in backpressure could increase fuel consumption and reduce available torque (Konstandopoulos et al., 2000).

Porous ceramic filter is an alternative structure to the honeycomb monolith which offered higher degree of porosity and larger surface area. It is brittle with closed, fully open or partially interconnected porosity and commercially accepted in many fields with variety of products such as catalysis, filtration, impact absorbing structures and biomechanical implants. In automotive industries, ceramic foams have received particular interest in the development of diesel particulate traps and catalytic converters. Meanwhile, in hydrocarbon absorber, zeolites are known for its ability to selectively absorb molecules based primarily on a size exclusion process (Amirnordin et al., 2007).

Novel diesel particulate filter (NDPF) is a combination of DPF and porous ceramic filter in the aim to curb soot and others gases from diesel engine. The potential of porous ceramic filter based on alumina and zeolite give higher reduction in emission from gasoline engine as a motivation to apply the filter as a new exhaust aftertreatment device for diesel engine.

REFERENCES

Alimin, A.J., 2006. *Experimental Investigation of a NOX Trap using Fast Response Emissions Analysers*. Coventry University.

Amirnordin, S.H. et al., 2007. *Porous Ceramic/Zeolite in Engine Exhaust Treatment*. Report. Universiti Tun Hussein Onn Malaysia.

http://inventors.about.com/library/inventors/bldiesel.htm [Accessed Jan 2010].

ARB, 2008. *Appendix B: Diesel Engine Emission Control Technologies*. [Online] Available at: http://www.arb.ca.gov/regact/dieselrv/appb.PDF [Accessed December 2008].

Arcaklioglu, E. & Celikten, I., 2005. A Diesel Engines Performance and Exhaust Emissions. *Applied Energy*, 80, pp.11-22.

Arcaklioglu, E. & Celikten, I., 2005. A diesel engines performance and exhaust emissions. *Applied Energy*, 80, pp.11-22.

AUTOCHEK GAS AND SMOKE, 2010. *Productsdb.com*. [Online] Available at: http://www.productsdb.com/produkdetail.php?kpid=17&pkid=36&pid=3515 [Accessed Jan 2010].

B.B.Gosh et al., 2002. Control of SI Engine Exhaust Emission Using ZSM-5 Supported Cu-Pt Bimetals as a catalyst. *SAE International*, (2002-01-2147).

Bensaid, S., L.Marchisio, D. & Fino, D., 2010. Numerical simulation of soot filtration and combustion within diesel particulate filters. *Chemical Engineering Science*, 65, pp.357-63.

Blakeman, P.G., Chandler, G.R., John, G.A. & Wilkins, A.J.J., 2001. Investigations into NOX aftertreatment eith urea SCR for light duty diesel vehicles. *Society of Automotive Engineers*, 01(3624), pp.91-100.

Bosch, 2000. *Automotive Handbook 5th Edition*. Robert Bosch GmbH.

C.Born & N.Peters, 1998. Reduction of soot emission at a DI diesel engine by additional injection of hydrogen peroxide during combustion. *SAE Technical Paper Series*, 982676, pp.1-6.

Carel, R.S., 1998. *Health Aspects of Air Pollution, Handbook of Air Pollution from Internal Combustion Engines: Pollutant Formation and Control*. Academic Press.

Cherng, Y.L., 2002. Reduction of particulate matter and gaseous emission from marine diesel engines using a catalyzed particulate filter. *Ocean Engineering*, 29, pp.1327-41.

D.E.Hall et al., 1998. A review of recent literature investigating the measurement of automotive particulate; the relationship with environmental aerosol, air quality and health effects. *SAE Technical Paper Series*, 982602, pp.1-10.

Department of Environment, 2004. ISBN 983-9119-77-X *Annual Report 2004*. Periodicaly. Ministry of Natural Resources and Environment Malaysia.

Department of Environment, 2007. *Environmental Quality Act 1974, Environmental Quality (Control of Petrol and Diesel Properties) Regulations.* [Online].

Department of Environment, 2008. *Air Quality*. [Online] Available at: http://www.doe.gov.my/files/u1/AIR%20QUALITY.pdf [Accessed Jun 2010].

Department of Environment, 2008. *Pollution Sources Inventory*. [Online] Available at: http://www.doe.gov.my/files/u1/POLLUTION SOURCES INVENTORY.pdf [Accessed Jun 2010].

Enhance emissions and safety test, 2008. *Diesel Background*. [Online] Available at: http://www.vehicletest.state.mq.us/dieselbg.html.

Federal Subsidiary Legislation, 1996. *Environmental Quality Act 1974*. [Online].

G.Alkemade, U. & Schumann, B., 2006. Engines and exhaust after treatment system for future automotive applications. *Solid State Ionics*, 177, pp.2291-96.

Gill, A.P., 1988. Design Choices for 1990's Low Emissions Diesel Engines. *SAE Paper* , (880350).

Greening, P., 2001. European vehicle emissions legislation - present and future. *Topics in Catalysis*, 16(17), pp.5-13.

Hayashi, H. & Kubo, S., 2008. Computer simulation study on filtration of soot particles in diesel particulate filter. *Computers and Mathematics with applications*, 55, pp.1450-60.

Herrmann, H.O. & Durnholz, M., 1995. Development of a DI-Diesel Engine with Four Valve for Passenger Car Engines. *SAE Paper*, (950808).

I.Bertelsen, B., 2001. Future US motor vehicle emission standards and the role of advanced emission control technology in meeting those standards. *Topics in Catalysis*, 16(17), pp.15-22.

Jabatan Alam Sekitar, 2002. Kawalan Pelepasan daripada Enjin Diesel. August.

K.Higashimaya et al., 2003. A Catalyzed Hydrocarbon Trap Using Metal-Impregnated Zeolite for SULEV System. *SAE International*.

Koebel, M., Elsener, M. & Madia, G., 2001. Recent advances in the development of urea-SCR for automotive applications. *Society of Automotive Engineers* , 01(3625), pp.101-10.

Konstandopoulos, A.G. et al., 2000. *SAE Paper*.

Kostoglou, M., Housiada, P. & G.Kostandopoulos, A., 2003. Multi-channel simulation of regeneration in honeycomb monolithic diesel particulate filters. *Chemical Engineering Science*, 58, pp.3273-83.

Lambert, C., Vanderslice, J., Hammerle, R. & Belaire, R., 2001. Application of Urea SCR to Light Duty Diesel Vehicles. *SAE Papers*, (2001-01-3623), pp.85-90.

Lepperhoff, G., 2001. Influences on the particles size distrubution of diesel particulate emissions. *Topics in Catalysis*, 16/17(1), pp.249-54.

Lifeng, X., Graham, G. & McCabe, R., 2007. A NOx trap for low-temperature lean –burn-engine applications, Chemical Engineering Department, Ford Research and Innovation Center, Dearborn, USA, March 2007. *Catalysis Letters*, 115(3), pp.108-13.

M.W.Vincent, P.Richards & S.L.Cook, 1998. Particulates reduction in diesel engines through the combination of a particulate filter and fuel additive. *SAE Technical Paper Series*, 982654, pp.1-12.

Martirosyan, K.S., K.Chan & Luss, D., 2010. Behaviour features of soot combustion in diesel particulate filter. *Chemical Engineering Science*, 65, pp.42-46.

Matthews, R.D., n.d. Energy and Power. In M. Kutz, ed. *Mechanical Engineers Handbook*. third ed.

Monaghan, M.L., 1996. High-Speed Direct Injection Diesels - Present and Future Perspectives. In *Mech. E. London Seminar on Lean Burn Combustion Engines*. London, 1996.

Pierpont, D.A. & Reitz, R.D., 1995. Effect of Injection Pressure and Nozzle Geometry on Emissions and Performance in a D.I. Diesel. *SAE Paper 950604*.

Plint, M. & Martyr, A., 2001. *Engine Testing Theory and Practice*. second edition ed. Society of Automotive Engineers, Inc.

Pundir, B.P., 2007. *Engine Emissions Pollutant Formation and Advances in Control Technology*. India: Alpha Science International Ltd.

Richards, R.R. & Sibley, J.E., 1988. Diesel Engine Emissions Control for the 1990's. *SAE Paper*, (880346).

Road Transport Department, 2008. *Statistic*. [Online] Available at: http://www.mot.gov.my/stat/darat/mac%201.3.pdf.

S.Dhara & P.Bhagarva, 2003. A Simple Direct Casting Route to Ceramics Foams. *Journal of the America Society*, 86(1645 - 1650).

S.Sharafat et al., 2006. Breeder Foams: An Innovative Solid Breeder Material for Fusion Application. *Journal of American Ceramic Society*, 81, pp.455-60.

Shaefer, F. & Basshuysen, R.V., 1995. *Reduced Emissions and Fuel Consumption in Automobile Engineering*. Vienna, New York: Springer-Verlag.

Shah, J.J., Nagpal, T. & Brandon, C.J., 1997. *Urban Air Quality Management Strategy in Asia - Guidebook*. Washington D.C: The World Bank.

Socalevo.net, 2010. *forum*. [Online] Available at: http://www.socalevo.net/forum/index.php?PHPSESSID=aa2bf81bf03586b3d9ed74bc9fc7148f&topic=80032.msg7692678 [Accessed Jan 2010].

Song, H., Ladommatos, N. & Zhao, H., 2001. Diesel Soot Oxidation under Controlled Conditions. *SAE Papers*, (2001-01-3673), pp.111-19.

Stumpp, G., Polach, W., Muller, N. & Warga, J., 1989. Fuel Injection Equipment for Heavy Duty Diesel Engines for US1991/1994 Emissions Limit. *SAE Paper*, (890851).

Suzuki, J. & Matsumoto, S., 2004. Development of Catalyst for Diesel Particulate NOx Reduction. *Topics in Catalysis*, 28(1-4), pp.171-76.

US Department of Technology, 2008. Freedom Car and Vehicle Technologies Program.

Wellington, B. & Asmus, A., 2002. *Enjin Diesel dan Sistem Bahan Api edisi keempat*. Translated by Y. Ramli, M.N. Mohd Ja'afar, C.A. Che Ismail & R. Abu Bakar. Penerbit Universiti Teknologi Malaysia.

Wu, C.-H.G. & Hammerle, R., 2001. An On-Board Reductant Delivery System for Diesel Aftertreatment. *SAE Paper*, (2001-01-3622), pp.79-84.

Yamamoto, K., Satake, S. & Yamashita, H., 2009. Microstructure and particle-laden flow in diesel particulate filter. *International Jurnal of Thermal Science*, 48, pp.303-07.

Zulkifli, A.M., Zulkefli, Y., Rahmat, M. & Yasmin, A.K., 2002. Managing our environment through the use of clean fuel. In *Proceedings of the Regional Symposium on Environment and Natural Resources*., 2002.